An ultrasound study of lingual coarticulation in children and adults

Research Report for ESRC research grant RES-000-22-2833
1 May 2008 - 30 April 2009
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July 2009

Background

The aims of this project were to establish how children's patterns of coarticulation differ from adults', and to attempt to explain the observed coarticulatory patterns, as well as the nature and the degree of variability found in children and adults.

Why study coarticulation development?
Coarticulation refers to the articulatory overlapping of adjacent sounds in speech. An example of coarticulation is the measurable and perceivable difference between two realisations of the consonant /s/, in the syllables /si/ and /su/, arising from the influence of the following vowel. Adults without speech disorders manifest a certain extent of articulatory overlap, typical for a given language and acceptable to listeners. Appropriate coarticulation is indicative of mature control of articulators during speaking. The information about developmental paths taken by children to adult-like motor control of speech is very important for many different disciplines including phonetics, linguistics, developmental psychology, and speech and language therapy. However, there are still crucial gaps in our knowledge in this area. A recent literature review claims that "there is a real paucity of studies of oral motor development for speech. There are very few laboratories doing work in this area, and this is surprising given the importance of normal speech development in human experience" (Smith, in press).

It has been shown in previous research on typical speech development that "the amount of coarticulatory overlap changes during the developmental process from babbling, to infant speech, and to fully mature speech. Thus, coarticulation phenomena can tell us something about speech motor control and speech motor development" (Ziegler & Maassen 2007, p. 438). Evidence from disordered speech acquisition suggests that maturation of control is impaired in disordered children. Recent research on speech disorders (e.g., Nijland et al. 2002; 2003a; 2003b) showed significant differences in coarticulation between children with typically developing and disordered speech. Speech production of children with developmental apraxia of speech was reported to be "not only delayed but also deviant" (Nijland et al. 2002, p. 481; see also review in Hardcastle & Tjaden 2008). In order to establish to what extent deviant speech differs from the range of normal variability, and to undertake accurate diagnosis and subsequent successful treatment of speech disorders, it is necessary to have data on typical speech development. This study addressed tongue control maturation, by comparing anticipatory coarticulation in children and adults.

Ultrasound as a method for studying coarticulation development
Studies of speech motor control have addressed coarticulatory processes occurring in various parts of the speech system (for a comprehensive review, see Hardcastle & Hewlett 1999). Particularly challenging for imaging and quantification is lingual coarticulation (e.g., Recasens 1999). The tongue is an internal articulator; the

configuration of its whole surface influences the acoustic characteristics of the sounds produced during speech, and therefore correct perception by the listeners. There are difficulties involved in imaging internal articulators; it is particularly hard to find instrumental techniques for recording tongue movements in young children. Most previous studies of the acquisition of coarticulation relied heavily on acoustic analysis, which provides only indirect evidence of articulatory movements; sometimes, the acoustic signal is not even present; for example, during closure of voiceless stops. In children's speech, acoustic analysis is particularly problematic, due to the high fundamental frequency and the presence of many non-modal phonations, leading to potential difficulties with formant tracking (e.g., Buder 1996; Assmann & Katz, 2000).

Ultrasound is a safe and non-invasive articulatory technique, and it provides information about the shape of most of the midsagittal tongue contour, including the root (e.g., Stone 2005; Wodzinski & Frisch 2006; Davidson 2007; Vazquez Alvarez & Hewlett 2007; Zharkova 2007a; 2007b; Gick et al. 2008; Kocjančič 2008; Lawson et al. 2008; Zharkova & Hewlett 2009). Ultrasound has a number of advantages over other articulatory techniques for analysing coarticulation, notably electropalatography (EPG) and electromagnetic articulography (EMA). Both EPG and EMA are relatively invasive: EPG requires the user to wear a special artificial palate, and EMA uses small coils fastened to the tongue surface. Besides, EPG only shows the place on the hard palate where tongue-palate contact occurs; it does not provide information on tongue shape. EMA only provides information on displacement of a few points on the tongue, "which may or may not include the tongue portion used to make a consonantal constriction" (Fowler & Brancazio 2000, p. 4). Ultrasound offers a direct representation of tongue movements in speech, and it allows for viewing most of the tongue contour. Figure 1 is an example of an ultrasound image of a child's tongue. The lower edge of the bright white curve is the surface of the tongue. The tongue tip is on the right and the black area beyond it is caused by the bone of the chin. The black area in the lower left of the figure is caused by the hyoid bone.

Figure 1. Ultrasound frame at the middle of the consonant /ʃ/ from the word "shah" produced by a child speaker. Distance is in cm and the origin of the scale is at bottom left. The line of brightness in the ultrasound image represents the tissue-air interface at the tongue surface.

The present work for the first time used direct ultrasound imaging of tongue movements to analyse child and adult productions. The project has developed a methodology for the comparison of lingual coarticulatory properties in children and adults.

Acquisition of coarticulation by children
Past studies have produced conflicting results on coarticulation in children and adults. Some acoustic studies reported findings suggesting that children coarticulate less than adults (e.g., Thompson & Hixon 1979; Kent 1983; Sereno & Liberman 1987). The findings on stronger coarticulation in adults have been taken as evidence that child productions may be more “segmental” than adult productions, i.e., individual speech sounds are produced by children with less articulatory overlap than by adults. Some studies reported no significant differences between adults and children, based on acoustic data (e.g., Sereno et al. 1987; Flege 1988; Katz et al. 1991). For example, Flege (1988) found that anticipatory nasal coarticulation was strong in both children and adults, and concluded that “children’s speech was not more ‘segmental’ than adults’” (p. 525). A number of experimental works reported that children coarticulate *more* than adults (e.g., Nittrouer et al. 1989; 1996; Siren & Wilcox 1995; Nijland et al. 2002). Such results have been interpreted to suggest that in consonant-vowel syllables, children initiate their vowel gestures earlier in the syllable, and that “the phonetic segment is the endpoint rather than the starting point of development” (Nittrouer et al. 1996, p. 380).

It has been reported in a number of works that within-speaker variability is greater in children than in adults (e.g., acoustic studies: Kent & Forner 1980; Sharkey & Folkins 1985; Nittrouer 1993; Lee et al. 1999; Nijland et al. 2002; Nittrouer et al. 2005; articulatory studies of lip and jaw displacement: Smith & Goffman 1998; Walsh & Smith 2002; Riely & Smith 2003). Studies of within-group variability demonstrated by children and adults have produced equivocal results (e.g., Sereno & Liberman 1987; Sussman et al. 1992; Nijland et al. 2002). It has also been shown that the ability to separately control parts of the tongue improves with age (e.g., Gibbon 1999; Goozée et al. 2007; Gick et al. 2008). In this project, we analysed articulatory data on extent of coarticulation, within-speaker and within-group variability in lingual coarticulation in children and adults, in order to discover whether constraints on coarticulatory processes are different in children and adults.

Objectives

Both objectives of the study were met. The objectives were as follows:

<u>Objective 1:</u> to compare coarticulation patterns in children and adults using synchronised ultrasound and acoustic data.

The following research question was linked to this objective:
- Do children demonstrate a significant difference from adults in coarticulatory patterns, and if there is a significant difference, what is the direction of the difference?

<u>Objective 2:</u> to compare degree of variability of children’s coarticulatory patterns with those of adults.

The following research question was linked to this objective:
- Do children exhibit significantly greater within-speaker variability than adults in their temporal and spatial patterns of coarticulation?

The following two sections of this report (Methods and Results) outline how these objectives were achieved.

Methods

The participants, all native speakers of Standard Scottish English, were eleven normally developing children aged five to nine years (see Table 1 for child ages), and eleven adults (mean age 34 years old; standard deviation 5.8 years).

Participant	Age	Sex
Child 1	8;4	Male
Child 2	6;10	Female
Child 3	6;4	Male
Child 4	8;6	Male
Child 5	9;7	Male
Child 6	6;3	Male
Child 7	6;9	Female
Child 8	6;7	Female
Child 9	9;9	Female
Child 10	7;7	Female
Child 11	5;10	Male

Table 1. Details of child participants. Ages are reported as [years;months].

The data were consonant-vowel (CV) syllables including all CV combinations of the following segments: /s/, /ʃ/, /i/, /u/ and /a/. The syllables were produced in the carrier phrase “It’s a … Pam”. The target syllables were spelt as “she”, “shoe”, “shah”, “sea”, “Sue” and “sah”; the sentences were shown to the participants on the computer screen, accompanied by images corresponding to the target syllables. The participants were first familiarised with the data; the latter two syllables were introduced as names of inhabitants of another planet. Every target was repeated ten times. The total number of tokens of the CV syllables recorded was 1320 (22 participants x 6 CV types x 10 repetitions).

Synchronised ultrasound and acoustic data were collected using the Queen Margaret University (QMU) ultrasound system (Articulate Instruments Ltd 2007, 2008; Scobbie et al. 2008; Wrench and Scobbie 2008). A photograph of a child participant wearing a transducer-stabilizing headset is presented in Figure 2. The internal ultrasound scan rates in the recordings varied between 50 and 100 Hz. Ultrasound images were transferred into the computer at NTSC video output rate of 30 Hz.

Figure 2. A photograph of a child participant wearing a purpose-designed headset for stabilizing the ultrasound transducer in relation to the head. A head-mounted microphone is attached to the headset.

The methodology for analysing ultrasound data in this project was adapted from Zharkova & Hewlett (2009), to enable comparative analysis of child and adult data. Ultrasound frames at two time points, the mid-point of the consonant and the mid-point of the vowel, were identified in each of the different consonant-vowel sequences, based on the acoustic data. At each time point, a cubic spline was automatically (with subsequent manual correction) fitted to the tongue surface contour. Each spline was defined in terms of x-y coordinates, and these coordinates were used for comparing tongue curves. Tongue curve comparison was based on nearest neighbour calculations (see Annex 1).

For ten adult speakers (Adult 1 – Adult 10) and for ten child speakers (Child 1 – Child 10), for the consonant /ʃ/ in each pair of vowel contexts, MC values across ten tokens were obtained. In order to address Objective 1, MC values were compared across age group and vowel pair. Objective 2 was addressed by calculating within-speaker coefficients of variation for MC, separately for each participant and each vowel pair, across ten tokens. Coefficients of variation were compared across age group and vowel pair. In order to observe and explain the nature and the degree of variability found in children and adults, MC values were plotted separately for each participant; also, within-group coefficients of variation were calculated for each group of speakers, in each vowel context.

Results

Comparison of coarticulatory patterns in children and adults (Objective 1)

In this study, a significant main effect of age group on MC was reported ($F = 78.51$; $df = 1$; $p < 0.001$). On average, MC was greater in children than in adults (mean MC of 0.88 in children versus mean MC of 0.83 in adults), suggesting that children had greater anticipatory lingual coarticulation. This finding is in agreement with the results of previous studies that have reported greater coarticulation in children than in adults (e.g., Nittrouer et al. 1989; 1996; Siren & Wilcox 1995; Nijland et al. 2002). Table 2 presents MC values for /ʃ/ for children and adults, across vowel pairs.

	a/i	**a/u**	**i/u**
Children	1.05 (*0.26*)	0.92 (*0.29*)	0.66 (*0.23*)
Adults	1.05 (*0.13*)	0.98 (*0.18*)	0.44 (*0.18*)

Table 2. Magnitude of Coarticulation values for children and adults, in three different vowel contexts; standard deviations are in brackets.

In all speakers /ʃ/ had stronger coarticulation in the context /a/-/i/ than in the context /i/-/u/. There was a significant difference in MC across vowel pairs ($F = 2821.93$; $df = 2$; $p < 0.001$), with the pair /i/-/u/ affecting the consonant the least, and the pair /a/-/i/ producing, on average, the greatest effect. This result is most likely related to the fact that the distance between tongue contours for /a/ and /i/ was greater, in each speaker (both in children and adults), than the distance between tongue contours for /i/ and /u/.

The difference between children and adults in the extent of coarticulation was shown to be dependent on the vowel context (the interaction between age and vowel context was significant: $F = 215.18$; $df = 2$; $p < 0.001$). This finding agrees with Boucher (2007), who found that child-adult differences in extent of consonant-on-vowel coarticulation depended on the consonant type. In the present study, the consonant /ʃ/ was coarticulated differently in children and adults, depending on the vowel pair chosen as the conditioning environment.

The greater coarticulation in children than in adults in the context /i/-/u/ (see Figure 3, where tongue curves from Child 3 and Adult 8 are presented) was partly due to the fact that the tongue during /ʃ/ was very close to its position during the following vowel. In adults the tongue during /ʃ/ was generally at a noticeable distance from its position for the following vowel. Therefore, it is possible to say that in the /i/-/u/ context, in adults the tongue during /ʃ/ adapted to the following vowels less than in children.

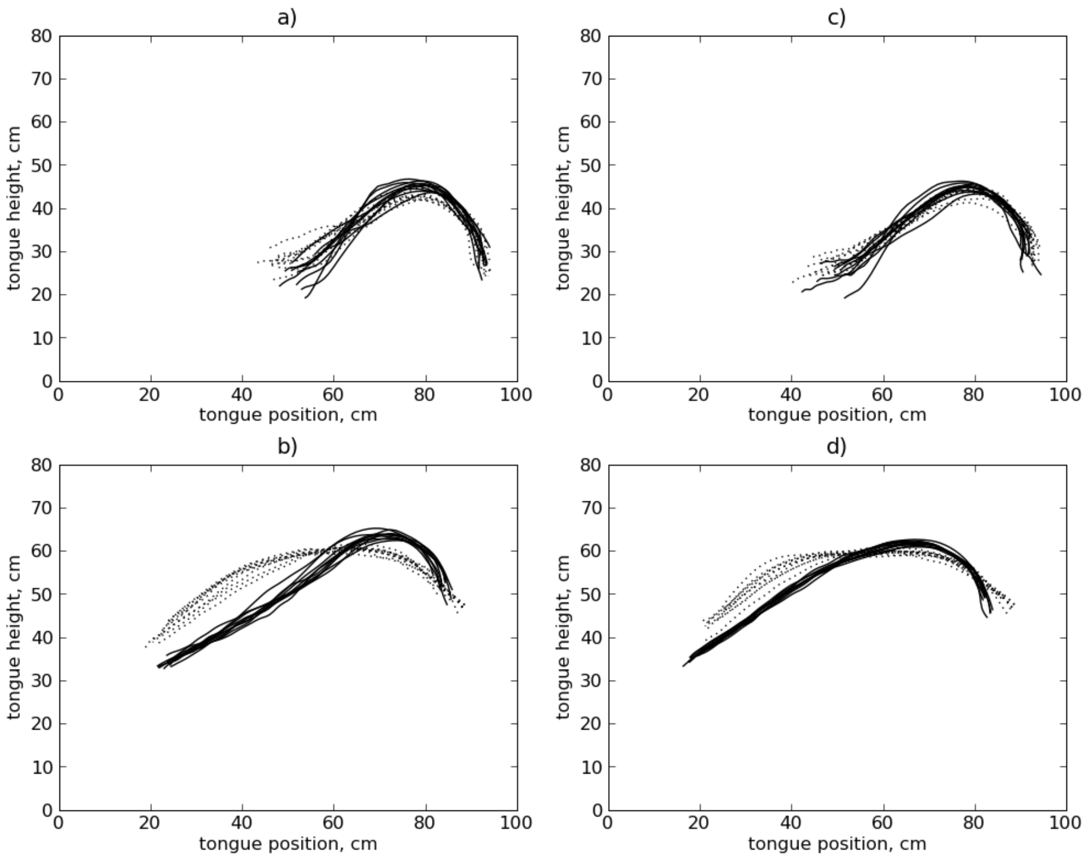


Figure 3. Tongue contours for /ʃ/ from /ʃi/ (dotted) and /i/ from /ʃi/ (solid): a) Child 3; b) Adult 8. Tongue contours for /ʃ/ from /ʃu/ (dotted) and /u/ from /ʃu/ (solid): c) Child 3; d) Adult 8.

The difference between children and adults in the context /a/-/u/ was in the opposite direction. Children, on average, had smaller coarticulation in /a/-/u/ context than adults. The plots in Figure 4 show differences in production of the vowels by the children and adults which may go some way to explaining the differences in coarticulation. Figure 4 (*a* and *b*) shows tongue contours for the vowels /a/ and /u/ from /ʃa/ and /ʃu/, respectively, in one child (Child 8) and one adult (Adult 2). This distance, in the formula for MC, is proportionate to the extent of coarticulation. The plots show that the distance between the two vowels is quite big in the adult, and relatively small in the child. This relative difference becomes more apparent when these plots are compared with the plots for the vowels /a/ and /i/ for the same speakers (Figure 4, *c* and *d*). The difference between the /a/-/i/ distance and the /a/-/u/ distance is much more noticeable in the child than in the adult. This child-adult difference is an illustration of the reported greater coarticulation in adults in the /a/-/u/ vowel context.

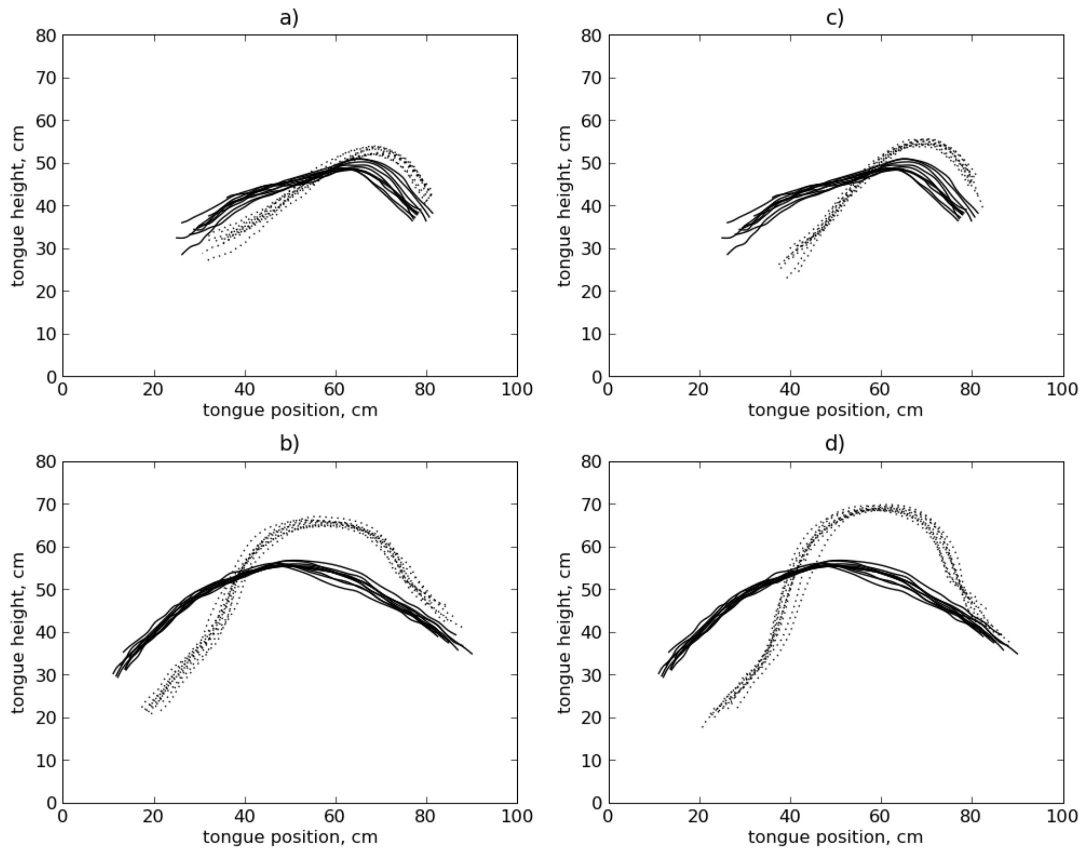


Figure 4. Tongue contours for /a/ from /ʃa/ (solid) and /u/ from /ʃu/ (dotted): a) Child 8; b) Adult 2. Tongue contours for /a/ from /ʃa/ (solid) and /i/ from /ʃi/ (dotted): c) Child 8; d) Adult 2.

Vowel contours for the /i/-/u/ context for the same two speakers are also displayed (Figure 5). It is clear from comparing Figure 4 (*c* and *d*) and Figure 5 that both in this child and in this adult the distance between the vowel contours for /i/ and /u/ was much smaller than the distance between the vowel contours for /a/ and /i/. This difference between the two vowel pairs was observed in all participants.

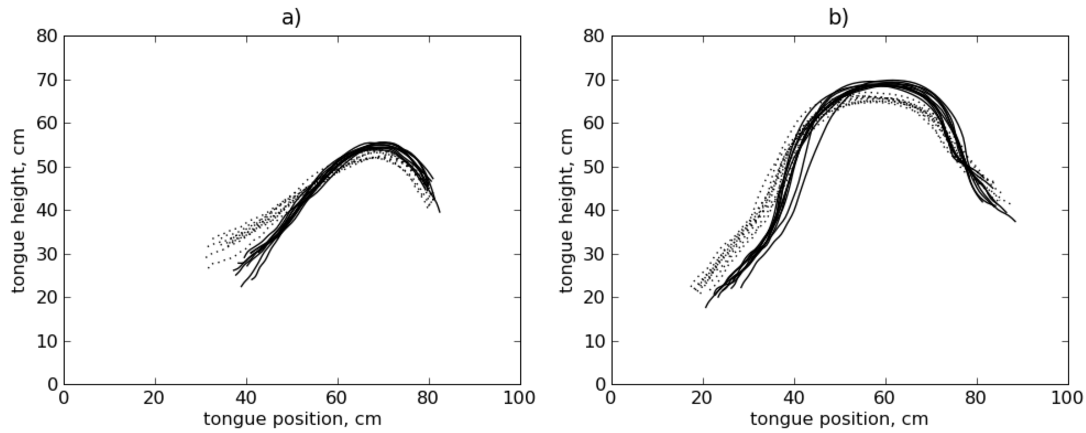


Figure 5. Tongue contours for /i/ from /ʃi/ (solid) and /u/ from /ʃu/ (dotted): a) Child 8; b) Adult 2.

The results presented above show that segmental context is important when describing differences in coarticulation between children and adults. Context-dependent differences between children and adults can also contribute to the debate on whether coarticulation is “syllabic” or “segmental” in children. Our results suggest that in typically developing children lingual coarticulation can be either of these two types, depending on the segmental context used to quantify coarticulatory effects.

Comparison of the degree of variability in children and adults (Objective 2)

A significant difference in the within-speaker coefficient of variation between adults and children was observed (F = 17.09; df = 1; p < 0.001). Table 3 illustrates greater values of the coefficient of variation in children.

	a/i	**a/u**	**i/u**
Children	14.72	21.32	27.38
Adults	9.89	11.18	20.24

Table 3. Within-speaker coefficient of variation values for children and adults, in three different vowel contexts.

Examples of individual variability are presented in Figure 6.

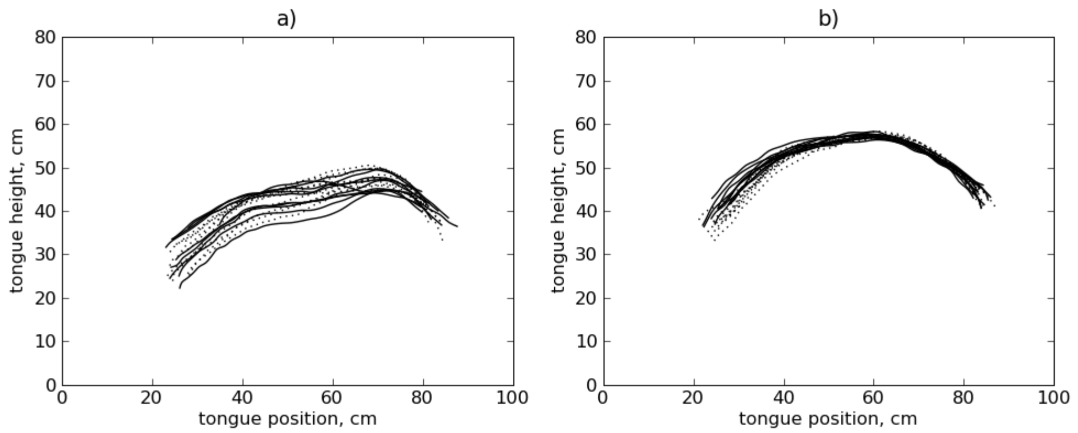


Figure 6. Tongue contours for /ʃ/ from /ʃa/ (solid) and /ʃ/ from /ʃi/ (dotted): a) Child 1; b) Adult 1.

Significantly greater within-speaker coefficients of variation in children than in adults show that adults and children differ in the degree of individual variability in coarticulatory patterns, children being more variable than adults. These results agree with existing literature (e.g., Kent & Forner 1980; Sharkey & Folkins 1985; Nittrouer 1993; Nijland et al. 2002; Nittrouer et al. 2005; Walsh & Smith 2002). There was no significant child-adult difference in coefficients of variation depending on the vowel context. This finding suggests that children are less consistent than adults in their productions of all segments analysed in the present work. Therefore, in our study, within-speaker variability of coarticulation reflected the child-adult difference better than the amount of coarticulation did. The strong within-speaker variability observed in this study may be because the children are still in the process of tuning their speech production system to the adult-like degree of trade-off between speed of tongue movement, speech timing and amount of tongue travel. Another possible contributor to the observed within-speaker variability in children might be related to the ultrasound system setup. Every effort was made to ensure that the ultrasound transducer was positioned steadily in relation to the head, for collecting multiple repetitions. The head sizes of all child participants in the study were big enough for the headset. However, the possibility cannot be excluded that more head movement occurred in children than in adults during the recording session. It is impossible to verify this in the current study. In future research, we intend to conduct a study involving correction for head movement (cf. Whalen et al. 2005; Scobbie et al. 2008).

Strong within-group variability in lingual coarticulation was found in both children and adults. There was also a noticeable difference between children and adults depending on the vowel context. In Figure 7, mean MC values for individual participants are presented, separately for each vowel context. It can be seen in the figure that in all participants, MC in the context /a/-/i/ is greater than in the context /i/-/u/. In all adults, MC values in the context /a/-/u/ are also greater than in the context /i/-/u/. It appears from the figure that children are more variable than adults in the contexts /a/-/i/ and /a/-/u/, but not /i/-/u/.

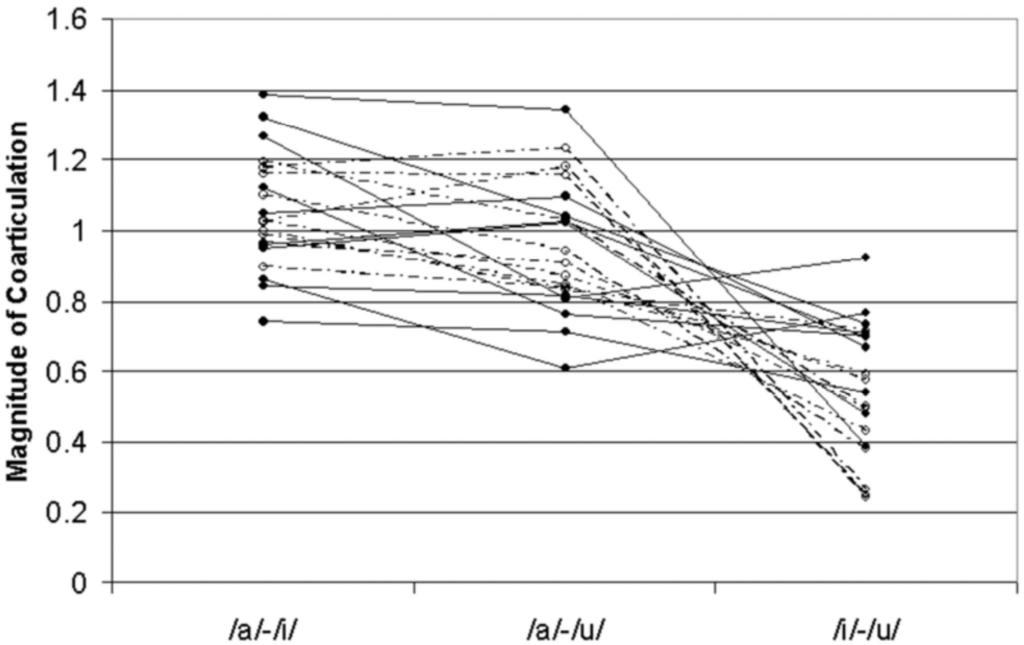


Figure 7. Magnitude of Coarticulation values for individual speakers: solid lines and filled circles – children; dashed-dotted lines and empty circles – adults.

Within-group coefficients of variation are presented in Table 4. The table confirms visual observations. It shows that in the context /a/-/i/ children were over two times more variable than adults. In the context /a/-/u/ the child-adult difference was smaller; in the context /i/-/u/ the pattern was the opposite: adults varied more than children. It is possible that children differ from each other in how they control tongue movement in the vertical dimension and thus the strong within-group variation in the children in /a/-/i/ and /a/-/u/ contexts is partly attributable to the inclusion in the data of vowels differing greatly in tongue height.

	a/i	a/u	i/u
Children	20.84	23.84	23.29
Adults	9.56	15.73	36.33

Table 4. Within-group coefficients of variation for children and adults, in three different vowel contexts.

Strong within-group variation in children in /a/-/i/ and /a/-/u/ contexts may partly be explained by the range of ages. Eight adults exhibited the most coarticulation in /a/-/i/ context, and the least coarticulation in /i/-/u/ context. This pattern was present in five children, four of them aged over eight years old. Two adults had stronger coarticulation in /a/-/u/ context than in /a/-/i/ context. This pattern was demonstrated by three children (Child 3, Child 7 and Child 10), all under eight years old. It is interesting that the only two children who exhibited a pattern not present in adult results, that is, stronger coarticulation in /i/-/u/ context than in /a/-/u/ context, were Child 2 and Child 6, both under seven years old. Data from more children would be helpful to establish how child-adult differences change with age.

Consonant-specific coarticulation in children and adults

Extent of adaptation of /s/ and /ʃ/ to the following vowel was compared in children and adults, using the data from a subset of speakers (six adults: Adult 1 – Adult 6; six children: Child 1 – Child 6). For each consonant, the distance between the consonant contours in each pair of vowel environments was calculated, for each speaker individually, and then compared across age group and consonant. In adults, consonant contours for /ʃ/ in different vowel environments were closer to each other than for /s/ (average distance 1.40 mm for /ʃ/ and 1.80 mm for /s/). In children the difference was in the same direction, but it was smaller (average distance 2.07 mm for /ʃ/ and 2.23 mm for /s/). An example is presented in Figure 8.

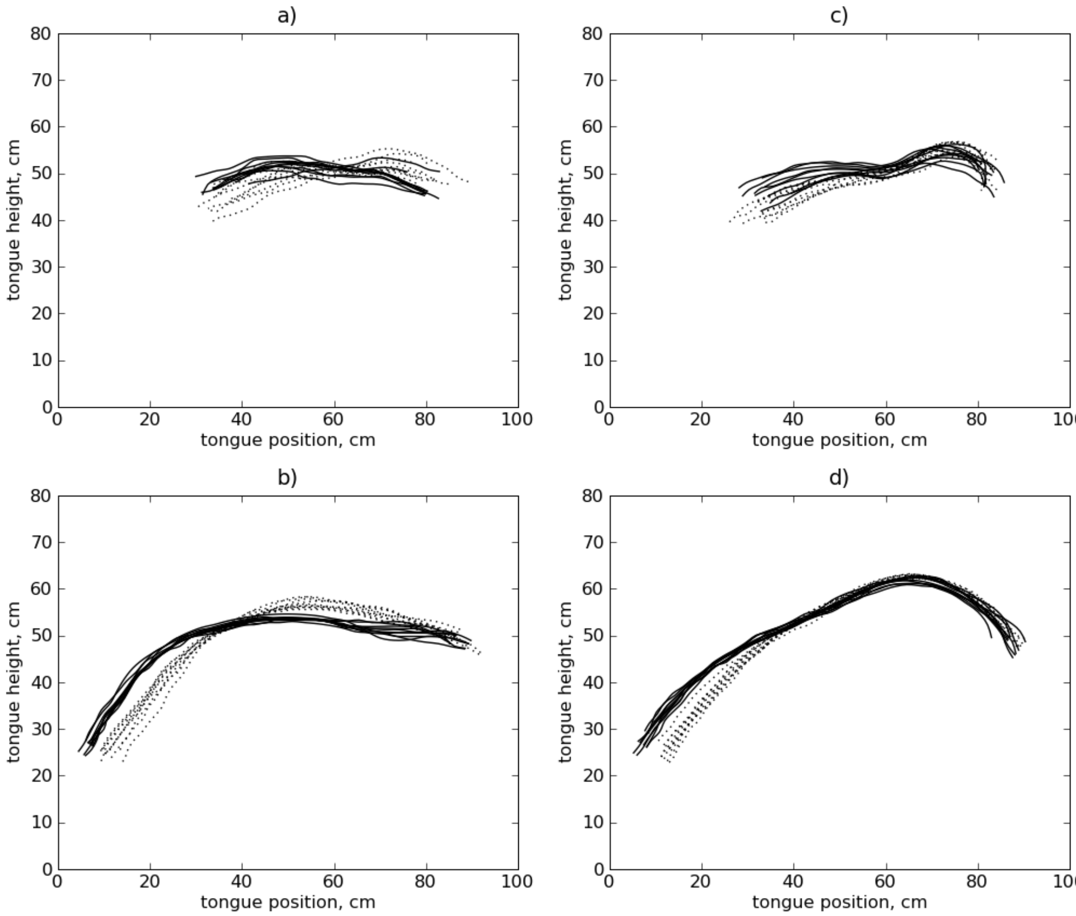


Figure 8. Tongue contours for /s/ from /sa/ (solid) and /s/ from /si/ (dotted): a) Child 2; b) Adult 3. Tongue contours for /ʃ/ from /ʃa/ (solid) and /ʃ/ from /ʃi/ (dotted): c) Child 2; d) Adult 3.

A significant interaction of age group and consonant was found (F = 27.60, df = 1, $p < 0.001$), suggesting that while in adults the two fricatives are coarticulated in a noticeably different way, children have not yet fully developed this consonant-specific feature of coarticulation. This finding supports the literature claims that children are less able than adults to separately control different parts of the tongue (Gibbon 1999; Goozée et al. 2007; Gick et al. 2008), and that children have relatively poor speech motor precision as compared to adults (e.g., Green et al 2000; Goffman et al. 2008). The ability to coarticulate speech sounds differently depending on constraints on specific parts of the tongue may increase with age, as the skill of separately controlling parts of the tongue improves. This analysis is being extended to include the data from all speakers.

Qualitative analysis of tongue dynamics

This project has provided some important unique qualitative information on dynamic changes in tongue shapes during consonants in different vowel environments. The QMU ultrasound system allowed us to use the process called "deinterlacing" in order to separate each consecutive ultrasound frame into two individual images. This process produced double the number of ultrasound frames (thus increasing the frame rate from 30 Hz to 60 Hz), and as a result it was possible to see a more detailed dynamic representation of tongue movements.

This study did not aim to conduct quantitative analysis using these dynamic high frame rate images. Some pilot qualitative analysis of dynamic changes in tongue shape during consonant-vowel syllables was carried out. The results of this analysis suggest that children and adults differ in relative timing of lingual gestures throughout the consonant-vowel sequence. In adult productions, the path of tongue shape change between the consonant and the vowel was noticeably different for the two fricative consonants, with little overlap, while in child productions, there was a strong overlap in the trajectories for the two consonants.

Further analysis of dynamic tongue configurations is being conducted. Such analysis can be used to expand the knowledge obtained from analysing coarticulatory patterns based on a single time point in a segment.

Activities

Presentations of the research results to the academic audience were as follows (see full details on the ESRC Society Today web page):
- 2 presentations at international conferences (1 oral, 1 poster);
- 2 oral presentations at linguistic phonetic specialist seminars in Edinburgh (also attended by speech and language therapists);
- 2 invited oral presentations abroad (at the University of Oslo and at the University College Cork), at seminars attended by academics and speech and language therapists.

During the invited visit to the University of Oslo, Natalia Zharkova ran a workshop on the use of ultrasound hardware and software for speech research.

In March 2009, Natalia Zharkova participated in the Madskillz workshop in Kirkcaldy, targeted at schoolchildren, their teachers and parents/carers (see Impacts for more details).

Outputs

All three publications referred to in the End of Award Report Form (Zharkova et al. 2008a; 2008b; submitted) are peer-reviewed.

An ultrasound/acoustic database of lingual articulation in children and adults has been recorded, and is stored in the Speech Science Research Centre at QMU, Edinburgh. The database is available for future research projects, it could be used to address further aspects of coarticulation development and other linguistic phonetic questions.

An article is in preparation, for submitting to a peer-reviewed journal. The article incorporates the latest results on child-adult differences in segment-specific coarticulation, and addresses the methodological aspect of speech development research.

A submission to Ultrafest VI (Ultrasound Meeting; 19-21 March 2010, Haskins Laboratories, Yale University, New Haven, CT, USA) is being prepared, based on the additional analysis of the data collected during the project.

A short communication about the project has appeared in the QMU staff internal newsletter, QM Inside ("Ultrasound technology helps researchers"; issue 12, June 2009, p. 2). Additional appropriate media coverage of the project has been discussed with the QMU Press Office.

Impacts

Impacts of the project include disseminating advanced knowledge in ultrasound analysis of speech to the academic and speech therapy community. These analysis techniques are now being introduced into clinical and non-clinical research at the Department of Linguistics, University of Oslo, and at the Department of Speech and Hearing Sciences, University College Cork. The results have been disseminated to speech therapists in Belfast who are interested in purchasing ultrasound equipment; discussions about possible ways of using the research results in therapy are ongoing.

The ultrasound/acoustic database collected in the project could be used for university teaching: for example, for demonstrations in lectures on language acquisition, or to provide data for student research projects undertaken as part of their degree. In the academic year 2008/2009, the database has already been used by a fourth year student in speech and language therapy at QMU for a BSc honours dissertation. The Department of Speech and Hearing Sciences, University College Cork has expressed interest in using the database for research.

The Madskillz workshop for schoolchildren in Kirkcaldy allowed schoolchildren, their teachers and parents/carers to see beatboxers' tongue movements in real time, using portable ultrasound scanners. Participants could also observe their own articulations. This event had very positive feedback from children, teachers and parents. Some parents whose children had experience of attending conventional speech therapy sessions claimed that ultrasound could have benefited their children, by providing direct visual feedback on their articulations. The QMU Press Office have been liaising with us, with a view to organising similar educational events for the local community.

Future Research Priorities

This project is intended as a precursor to a much larger investigation, which would provide an assessment of coarticulatory skills maturation, and would address the dynamics of consonant-vowel sequences. Results of this project have given rise to more research questions concerning child-adult differences in coarticulation and the nature of within-speaker and across-speaker variability.

The study has reported significant differences in lingual coarticulation and variability between children and adults. The results suggest that there may be varying paths in different children towards adult-like control of the tongue in consonant-vowel sequences. Our work has also produced some evidence to support the claim that adult speakers "seem indeed to have some freedom in coarticulatory behaviour which is beyond that attributable to anatomical differences" (Kühnert & Nolan 1999, p. 28). The data on within-group variability in our work (e.g., within-group variability in the context /i/-/u/, which was stronger in adults than in children) demonstrate that adults have different strategies for producing the same consonant-vowel syllable. These different strategies provide a non-uniform target for the children to master. Further studies of lingual coarticulation development are needed, including more participants and more speech segments.

There is some evidence in the literature (Walsh & Smith 2002; Riely & Smith 2003; Smith, in press) that children of the ages studied in the present work have not yet achieved the adult degree of precision in speech movement coordination. Based mainly on articulatory studies of lip and jaw displacement, Smith (in press) claims that adolescents also demonstrate differences from adult speech motor control; she suggests that adolescents achieve faster speech rates than children at the expense of smaller displacement of lips and jaw, while younger children have relatively larger articulator displacements accompanied by slow speech rates. The current project has provided a rationale for a study of tongue control in children, adolescents and adults; we do not know of any such studies to date.

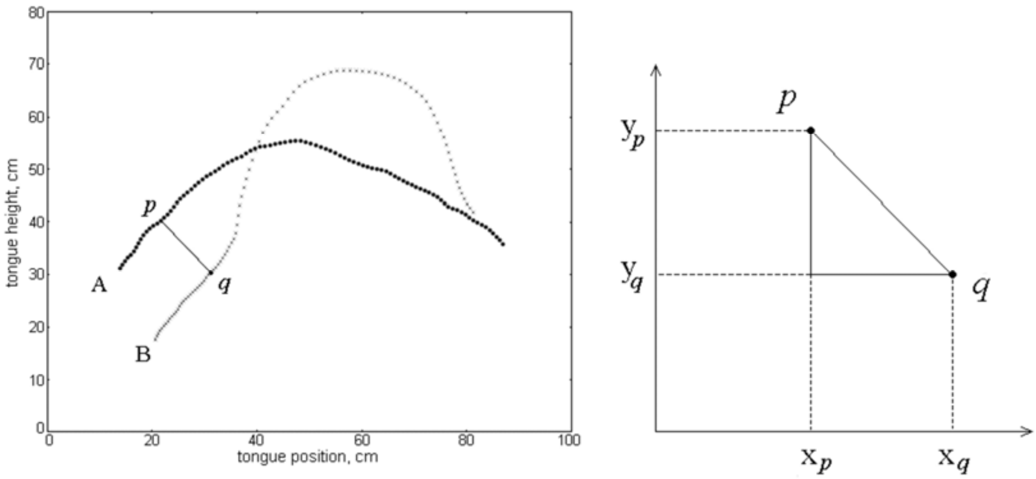
A research grant proposal has been submitted to the ESRC. The planned research project is based on the current project, it uses the methodology refined in the current project, and aims to compare coarticulation and tongue control in children, adolescents and adults. Larger numbers of speakers are planned to be recorded, and a larger number of speech sounds.

[4999 words]

Annex 1. Technical details on the methodology of comparing tongue curves

Distances between tongue curves

Tongue curve comparison in this project was based on nearest neighbour calculations (Zharkova & Hewlett 2009). In order to describe the process of calculating the distance between two curves, two x-y coordinates were arbitrarily chosen for illustration purposes (Figure 1a, *p* on curve A and *q* on curve B). The distance between two x-y coordinates is calculated using Pythagoras (see Figure 1b, which is an enlarged section of Figure 1a). The shortest distance from each x-y coordinate on one curve (e.g., from *p* on curve A) to the other curve (*q* on curve B) is calculated. Then all these shortest distances are averaged, and the resulting value represents the mean distance between the two curves.



a) b)

Figure 1. Illustration of a nearest neighbour distance. The point *q* on curve B is the nearest neighbour of the point *p* on curve A. The two curves in Figure 1a are taken from the vowel mid-point for two different vowels: /a/ (curve A) and /i/ (curve B).

Magnitude of Coarticulation

Magnitude of Coarticulation (MC) is the measure of coarticulation extent developed in this project. This measure of coarticulation expresses the ratio of the distance between the vowel contours (which is proportionate to the possible degree of consonantal adaptation offered by the two vowel contexts) and the sum of the consonant-vowel distances in each vowel environment (which is in inverse proportion to the degree of consonantal adaptation to the vowel contexts). The greater the MC value, the stronger is the coarticulatory effect produced on a given consonant by the two vowels. The following formula is used:

$$MC_C = \frac{V1 - V2}{(C_{V1} - V1) + (C_{V2} - V2)},$$

where C is the target fricative; V1 and V2 are two vowel phonemes providing the alternative conditioning environments; C_{V1} is C in the environment of V1; C_{V2} is C in the environment of V2.

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